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Wake detection in the turbine inflow using nacelle lidars

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Abstract. In this study we present the ability to detect wakes in the inflow of turbines using nacelle-mounted continuous-wave lidar systems. Wake flows generate small-scale turbulence, which has significantly smaller length-scales than ambient turbulence. Due to the lidars large probe volume this turbulence is attenuated and will not be visible in the lidar's measurements. One approach to retrieve information about small-scale turbulence is by measuring the lidar Doppler spectrum width. Here we present an wake detection algorithm based on these measurements at two distinct locations in front of the turbine. By comparing the line-of-sight turbulence intensity and considering the instantaneous misalignment it is possible to detect half- and full-wakes. This has been tested during a 4.5 month long experiment and results show that situations where the wake affects the lidar measurements can be removed.

1. Introduction

Coherent Doppler wind lidars are a novel anemometry devices, which offer the possibility of remotely sensing wind speeds. These devices are especially attractive for wind energy applications where wind measurements within the first few 100m of the boundary layer are required. Their spatial and temporal resolution allows measurements and flow characterization around utility-scale wind turbines [1, 2, 3]. Investigations of lidars mounted on top of the nacelle [4] or inside the spinner [5] to retrieve information about the turbine inflow have also been conducted. This led to a variety of proposed applications spanning from lidar-assisted yaw [6] and pitch control [7] over power curve validation [8] to wind farm control [9].

One of the problems associated with nacelle-mounted lidar systems is the limitation of only measuring the line-of-sight (LOS) component of the wind velocity. To obtain inflow information useful to control applications (like rotor-effective wind speed, yaw misalignment or vertical shear) reconstruction methods with appropriate wind models are necessary [10]. Usually the assumption of horizontal homogeneity is made. While being reasonable well satisfied in homogeneous, flat terrain, this assumption is heavily violated in complex terrain or when wakes impinge the field of view.

Thus it is necessary to detect flow situations where the assumptions of horizontal homogeneity is violated. An example of the severe influence of wakes on the misalignment measurement by a lidar system can be seen in fig. 1 and 2.



In fig. 1 three situations are illustrated. On the left horizontally homogeneous flow, which is aligned with the turbine, is shown. In this case the LOS components at each focus point are equal and the measured misalignment $\varphi = 0$. Once the flow is misaligned (the case of $\varphi > 0$ is shown in the center panel), the LOS component at the left focus point is reduced, while the right LOS component is increased. This leads to a measurement of $\varphi > 0$.

If the assumption of horizontal homogeneity is violated the wind vectors have different magnitudes even though the flow is aligned. A simplified situation is shown in the right panel of fig. 1, where a reduced speed is shown on the left side of the inflow. This can be caused by a wake, for example. Similar to the center panel this will cause a reduction of the LOS component on the left focus point and thus to a measured misalignment of $\varphi > 0$ despite an aligned flow.

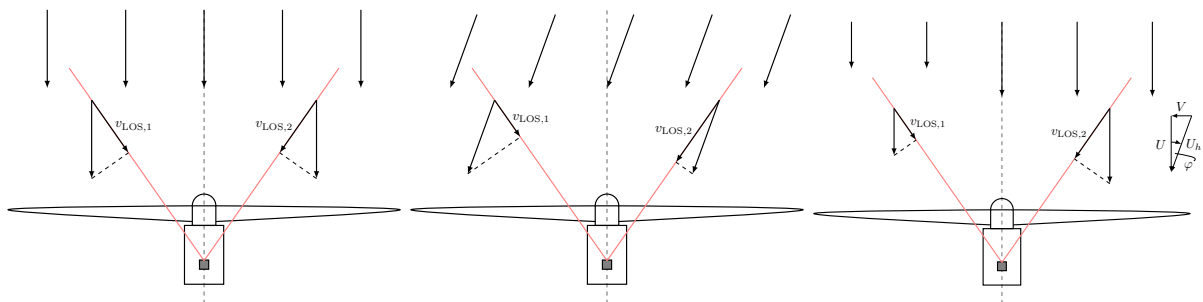


Figure 1. *Left:* Homogeneous inflow aligned with the turbine. *Center:* Homogeneous inflow misaligned with the turbine. *Right:* Impinging wake on the left part of the wind field.

The influence of wakes on experimental misalignment measurements can be seen in fig. 2. Here the 10 minute mean values are presented. The wake position of another upstream turbine is shown as a black vertical line. Outside the wake sector a average misalignment of around $+5^\circ$ can be observed. Inside the wake however, it can be seen that the misalignment varies substantially, reaching misalignments of up to $\pm 35^\circ$. This implies that it is crucial to detect waked situations, because the biased lidar measurements can lead to incorrect turbine alignment and thus energy losses.

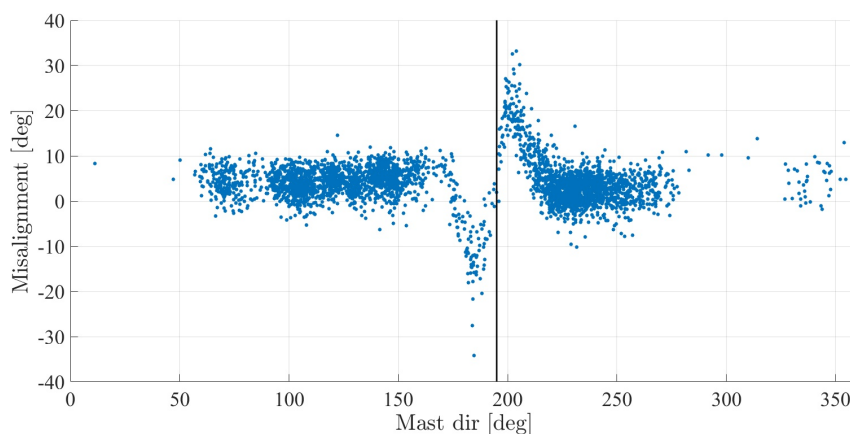


Figure 2. Turbine misalignment versus met mast wind direction; the vertical black line indicates a wake situation.

2. Methodology

In this study we want to show the possibility of detecting wake in the inflow of turbines using nacelle-mounted continuous-wave (cw) lidar systems.

The LOS wind speed can be expressed as a convolution of the LOS component of the wind vector and a weighting function φ :

$$v_r(\mathbf{r}) = \int_{-\infty}^{\infty} \varphi(s) \mathbf{n} \cdot \mathbf{u}(s\mathbf{n} + \mathbf{r}) ds. \quad (1)$$

Here \mathbf{n} is the beam unit vector, \mathbf{r} is a vector pointing to the focus position and \mathbf{u} is the 3-D wind vector field and s is the distance from the focus point along the beam. For a focused, cw, coherent lidar the weighting function (at large focus distances) can sufficiently be approximated by a Lorentzian distribution [11]:

$$\varphi(s) = \frac{1}{\pi} \frac{z_R}{z_R^2 + s^2}, \quad (2)$$

where z_R is the so-called Rayleigh length.

The wake detection methodology is based on two principles:

- (i) The length-scale of wake-generated turbulence is of significant smaller scale than ambient turbulence. This has been demonstrated by [12], where it was shown that the wake-added turbulence can be modeled by synthetic turbulence with a much smaller length scale than ambient turbulence. The models fit experimental observations well.
- (ii) Small-scale turbulence is responsible for increasing the width of a Doppler spectrum. Due to the large probe volume of a cw lidar small-scale fluctuations will be attenuated. The filtered turbulence will widen the Doppler spectrum. This has been experimentally verified by [13].

Combining these two principles, it is possible to define a wake detection parameter. Here we use the second centralized statistical moment v_s^2 of the Doppler peak, which is the spectrum variance, to estimate its width

$$v_s^2(t) = \frac{\int (v - v_r(t))^2 W(t, v) dv}{\int W(t, v) dv}, \quad (3)$$

where $v_r(t)$ is the wind speed measured by the lidar (see eq. 1), $W(t, v)$ is the Doppler spectrum as a function of time and LOS speed and v is an integration dummy.

To facilitate the detection the spectra variance is normalized by the LOS speed v_r to arrive at the LOS TI. By comparing these values from the two different beams, wakes in the inflow can be detected. The sign of the difference in LOS TI shows which half of the rotor is impinged by the wake. When high instantaneous LOS TI values compared to the averaged LOS TI are encountered a full wake is flagged.

An example of two different spectra, where one laser beam is measuring inside a wake, is shown in 3. Both spectra were obtained within 5 s. It can be seen that the blue spec has a much larger width indicating the presence of a significant amount of small-scale turbulence.

3. Experimental setup

A cw nacelle-mounted lidar by Windar Photonics is mounted on a Vestas V80 turbine. The device is a short-range lidar with a range of 80 m and can focus sequentially at two different focus locations with a angle of 60° in between. The measurement period spanned from beginning of November 2014 to mid of March 2015. A total of approximately 10,000 10-minute periods have been acquired. The site can be seen in fig. 4, where the turbine with the lidar systems is indicated by the marker. The surrounding turbine can also be seen.

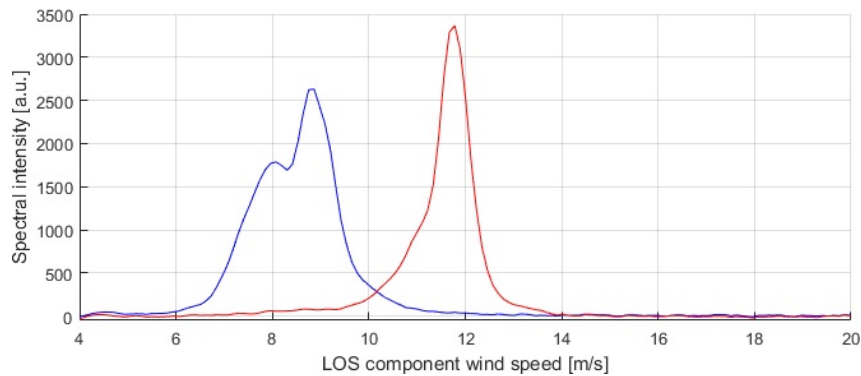


Figure 3. Example of two spectra where the blue spectrum show an enhanced peak width due to a measurement inside a wake.

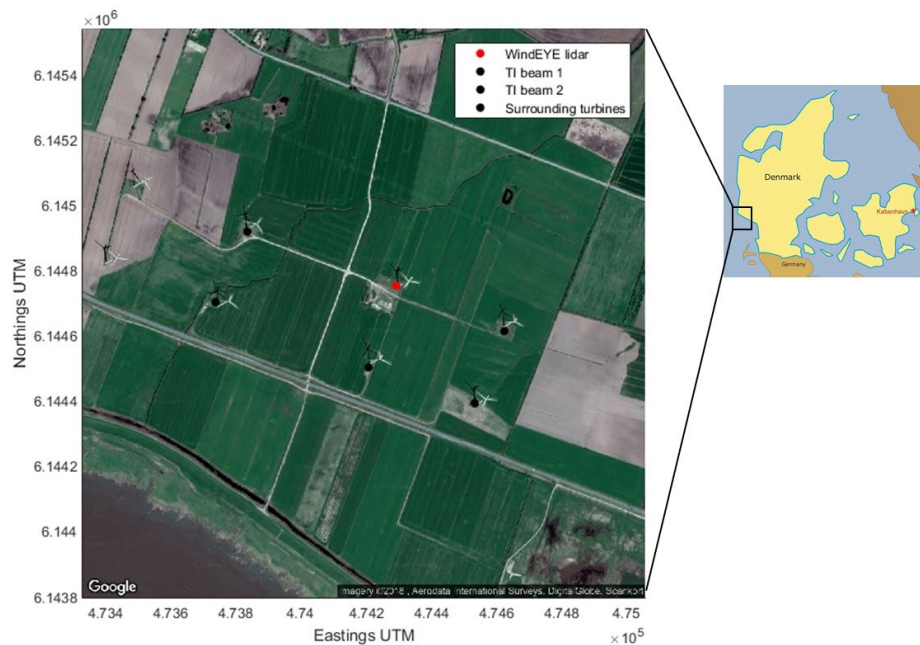


Figure 4. Google earth screen shot of the test site

4. Results

The results for the experimental campaign mentioned in the previous section can be found in fig. 5 and 6. The measurements are taken at a focus distance of 80 m. Firstly, the LOS TI as a function of yaw angle are shown. Here we have considered the wakes of the 5 closest turbines to the lidar-equipped turbine.

It can be observed from fig. 5 that the LOS TI is substantially higher at yaw angles when the turbine is pointing towards one of the surrounding turbines. Further when rotating clockwise, it can be seen that beam 2 will be affected first by the wake as this beam points to the right as seen from the turbine (compare fig. 1 again). So by comparing the difference in LOS TI can give information which side of the rotor is affected by the wake. Also, the LOS TI values for beam 2 have in general a lower value as for beam 1. The reason lies in the fact that the turbine is on average misaligned. The LOS wind speed on beam 2 is higher and thus reduces the LOS TI.

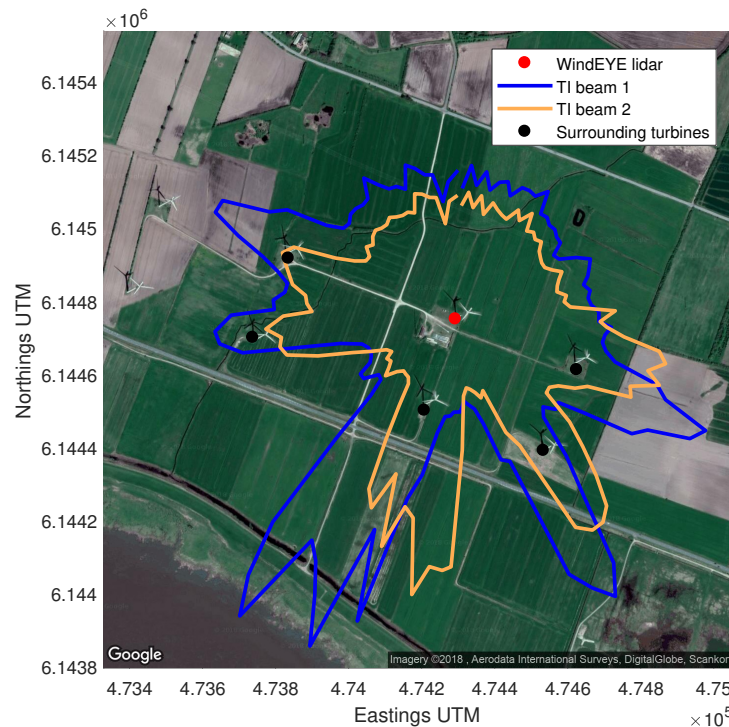


Figure 5. Map illustration of the LOS TI for beam 1 and 2. Solid points indicate the positions of the turbines.

Next, the performance of the wake detection algorithm is presented in fig. 6. The top panel shows the 10-minute mean misalignment of the turbine against its yaw position. The sinusoidal curves indicate the influence of wakes affecting the lidar measurements (compare to fig. 2). The surrounding turbines are shown as colored vertical lines and the sinusoidal influences of the wake are centered around them. Closer turbine tend to give more severe wake effects as the wind speed deficit has been recovered less compared to turbines further away.

The red, magenta and black scatter points show detected half- and full-wake situations, respectively. Here *Wake 1* refers to wake on the left half of the rotor (seen from the lidar) and *Wake 2* on the right half. It can be seen that the respective wake situations can be captured and a distinction between half- and full-wake is possible. There are some outliers, especially for the half-wake cases. It can probably attributed to non-wake sources of additional turbulence, like buildings or trees.

The bottom panel show the misalignment signal after all wake situations have been removed. Here it can be seen that it was able to remove the sinusoidal wake influences. Such a signal can be used for wind turbine yaw alignment.

5. Conclusion

Here we presented a methodology to detect wake situations in the inflow of turbines using 2-beam nacelle lidars. This is of importance since the assumptions made to derive wind field information from lidar measurements imply that a wake in one of the two beams is interpreted as a large misalignment. The Doppler peak width can be used to measure the small-scale turbulence found in wake flows. We showed results of a measurement campaign, where a wake detection algorithm has been tested. The results are promising and imply that it is possible to detect wake-affected turbine inflow. Thus, nacelle lidars can be used as turbine misalignment sensors. Future work

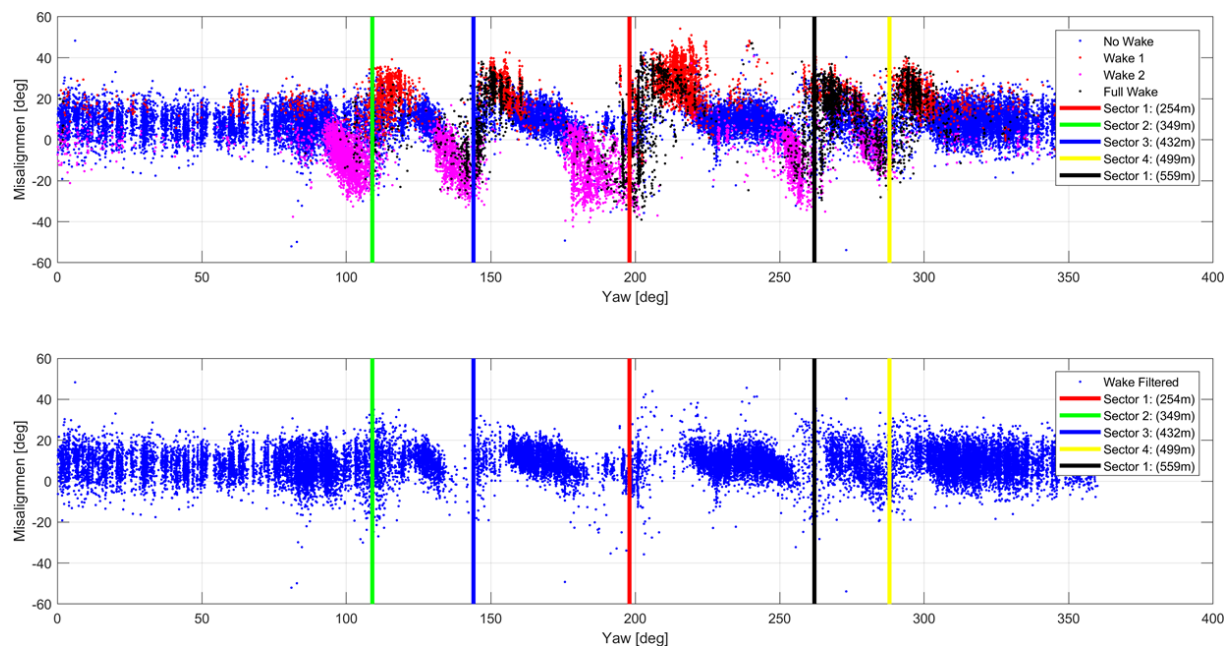


Figure 6. 10-minute mean turbine misalignment versus yaw position. Vertical lines indicate the surrounding turbines.

includes the analysis of different ambient turbulence levels. Interest lies in testing the algorithm in situations of high ambient turbulence, where the difference in peak width might not be as significant. Also we will investigate the possibility of not only detecting wake but to estimate the wake deficit simultaneously.

The learning objectives can be summarized as follows:

- Nacelle-mounted lidars can measure wind turbine misalignment, but wake situations include a bias in the measurements
- Wake turbulence is increasing the Doppler peak width of lidar measurements.
- By comparing the lidar Doppler peaks second centralized statistical moment wake flows can be detected in the inflow of turbines.
- A detection algorithm can be used to flag inflows affected by wakes and thus allowing a nacelle lidar to be used as a turbine misalignment sensor.

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